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Aeration optimization through operation at low dissolved oxygen concentrations: Evaluation of oxygen mass transfer dynamics in different activated sludge systems

Haitao Fan[1], *Lu Qi*[1,*], *Guoqiang Liu*[2], *Yuankai Zhang*[1], *Qiang Fan*[1], *Hongchen Wang*[1,*]

1. *Research Center for Low Carbon Technology of Water Environment, Renmin University of China, Beijing 100872, China*
2. *School of Environment, Jinan University, Guangzhou 510632, China*

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ABSTRACT

In wastewater treatment plants (WWTPs) using the activated sludge process, two methods are widely used to improve aeration efficiency — use of high-efficiency aeration devices and optimizing the aeration control strategy. Aeration efficiency is closely linked to sludge characteristics (such as concentrations of mixed liquor suspended solids (MLSS) and microbial communities) and operating conditions (such as air flow rate and operational dissolved oxygen (DO) concentrations). Moreover, operational DO is closely linked to effluent quality. This study, which is in reference to WWTP discharge class A Chinese standard effluent criteria, determined the growth kinetics parameters of nitrifiers at different DO levels in small-scale tests. Results showed that the activated sludge system could meet effluent criteria when DO was as low as 0.3 mg/L, and that nitrifier communities cultivated under low DO conditions had higher oxygen affinity than those cultivated under high DO conditions, as indicated by the oxygen half-saturation constant and nitrification ability. Based on nitrifier growth kinetics and on the oxygen mass transfer dynamic model (determined using different air flow rate (Q'_{air}) and mixed liquor volatile suspended solids (MLVSS) values), theoretical analysis indicated limited potential for energy saving by improving aeration diffuser performance when the activated sludge system had low oxygen consumption; however, operating at low DO and low MLVSS could significantly reduce energy consumption. Finally, a control strategy coupling sludge retention time and MLVSS to minimize the DO level was discussed, which is critical to appropriate setting of the oxygen point and to the operation of low DO treatment technology.

Introduction

Oxygen transfer from air to water is critical during the aerobic biological wastewater treatment process to ensure there is enough oxygen for microbial degradation and nutrient removal. Oxygen mass transport is achieved through the aeration system, which usually accounts for 45%–75% of total energy consumption in typical activated sludge process wastewater treatment plants (WWTPs) (Rosso et al., 2008). Reducing the energy consumption of aeration systems can therefore lead to significant reductions in total operating costs. In order to meet oxygen demand while ensuring low

* *Corresponding authors*. E-mails: qilu@ruc.edu.cn (Lu Qi), whc@ruc.edu.cn (Hongchen Wang).

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carbon operation, there needs to be a focus on improving aeration device efficiency and operating performance.

The main parameters used to evaluate oxygen mass transfer performance are the global oxygen transfer coefficient K_La, oxygen transfer efficiency (OTE) ε, and the standard oxygen transfer rate (SOTR), with these based on the two-film theory proposed by Lewis and Whitman (1924). The theory assumes that the main resistance to oxygen mass transfer occurs on the liquid film between the gas- and liquid-phase interface. Oxygen is a poorly soluble gas, and the oxygen mass transfer rate is therefore determined by the gas–liquid film transfer process. According to other theories, the oxygen transfer rate (OTR) can be enhanced by enlarging the gas–liquid interface area turbulence intensity (Fan et al., 2014). During actual operation of WWTPs, a high K_La value can be obtained in the following two ways: (1) adopting fine bubble diffusers with high performance, and (2) operating with a long sludge retention time (SRT) in order to weaken the negative effects of surfactants on oxygen transfer (Rosso and Stenstrom, 2006). There are actually many factors that affect K_La, and the most effective way to reduce energy consumption may not be simply replacing diffusers to improve the K_La value. As K_La increases, the aeration energy requirements tend to increase linearly (Oprina et al., 2010). Longer SRTs can lead to better removal of surfactants because of the diversity of microorganisms; however, the accompanying higher mixed liquor suspended solids (MLSS) will lead to serious deterioration in K_La with increasing liquid viscosity (Krampe and Krauth, 2003; Germain et al., 2007; Henkel et al., 2009a, 2009b; Fan et al., 2014). It is therefore crucial to comprehensively analyze the relationship between oxygen mass transfer dynamics and biomass properties during the aeration process.

In the case of biological nutrient removal (BNR), growth kinetic parameters are very important for designing aeration processes; these include the half-saturation constant, the decay rate of autotrophs, and the specific oxygen uptake rate (SOUR). If SOUR and nitrifier biomass concentrations are obtained, the oxygen uptake rate (OUR) can be calculated. OUR is closely related to influent quality and microbial respiration. Theoretically, 4.57 g of oxygen is needed to completely oxidize 1 g of NH_4^+-N into nitrate, with 3.43 g-O_2/g-N for first-step nitrification (ammonia oxidation) and 1.14 g-O_2/g-N for second-step nitrification (nitrite oxidation) (Metcalf and Eddy Inc., 2003). As biomass synthesis requires a small amount of ammonia as a nitrogen source, the specific oxygen demand for ammonia oxidation and nitrite oxidation reactions is lower than the aforementioned theoretical values (Rittmann and McCarty, 2001). It would be useful to more accurately determine the ammonia consumption and oxygen uptake of the nitrification process to construct oxygen demand and supply balances that enable better control of the air flow rate.

The oxygen demand and supply balance can be represented by operational dissolved oxygen (DO) concentrations, since these affect the oxygen mass transfer driving force and microbial respiration. A commonly used expression relating SOUR to the DO concentration is the Monod function, used to describe bacterial growth dynamics in wastewater treatment modeling and analysis (Monod, 1942). In the Monod function the growth rate is, with respect to a certain substrate (DO, chemical oxygen demand (COD), or ammonium) limiting for growth, being a monotonically increasing non-linear function that eventually approaches its maximum specific value at high substrate concentrations (Blackburne et al., 2007). Because of its non-linearity, in nitrification processes with low substrate concentrations, a small change in DO or ammonium concentration will have a larger effect on the nitrification rate. Low DO adversely affects the growth rates of ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB), and the kinetics among different nitrifiers are significantly different from each other (Schramm et al., 1999; Kim and Kim, 2006; Dytczak et al., 2008). However, according to the results of Liu and Wang (2013), in activated sludge systems with 10 and 40 day SRTs, complete nitrification was accomplished after long-term operation with DO values of 0.37 mg/L and 0.16 mg/L, respectively. From the above information, it is evident that there is significant energy saving potential when operating in low DO conditions.

Unnecessarily high airflow rates and DO concentrations should be avoided due to the decreased aeration efficiency and oxygen transfer this will cause (Olsson et al., 2005; Thunberg et al., 2009). In this study, diffuser performance was determined in a pilot scale test with different Q'_{air} and MLVSS values, and activated sludge dynamic properties were determined in small-scale tests using low (0.5 mg/L) and high (1 mg/L) DO conditions. Based on the results, we identify optimal DO points for different activated sludge systems, also developing a new control strategy coupling SRT and MLSS through the establishment of an oxygen supply and demand balance. Long-term and short-term aeration control paths are explained, to provide insights into how to set the DO control point to achieve minimum energy consumption while still complying with effluent criteria.

1. Materials and methods

1.1. Description of reactors and operating conditions

The experiment had two parts: tests of oxygen mass transfer dynamics and nitrifier growth kinetics tests.

Fig. 1a shows the reactor used for tests of oxygen mass transfer dynamics; this had a working volume of 10.6 m^3 (high = 7 m, ø = 1.5 m, effective water depth = 6 m). Oxygen mass transfer dynamic parameters (such as K_La values, OTE, and OTR) were determined using the process described in the standard methods for measurement of oxygen transfer in clean water (ASCE, 2000). Ceramic disc fine bubble diffusers (ø = 178 mm, pore size = 100 μm) were used for aeration. The airflow rate was adjusted to a target value with a calibrated rotameter. Anhydrous sodium sulfite was used to reduce DO concentrations to zero in test water. DO was measured with two LDO fluorescent DO electrodes (Tengue Instrument Co., Ltd., Beijing), which were placed in the column at depths of 1 m and 3 m below the water surface, respectively. DO data was stored online using a recorder and computer.

After the clean water test, a process test was performed following standard guidelines for in-process oxygen transfer testing (ASCE, 1997). Seed sludge was taken from the aeration tank of the Gao Beidian WWTP in Beijing; this WWTP uses a typical anaerobic–anoxic–aerobic (A^2O) process to treat municipal wastewater, with good performance through complete

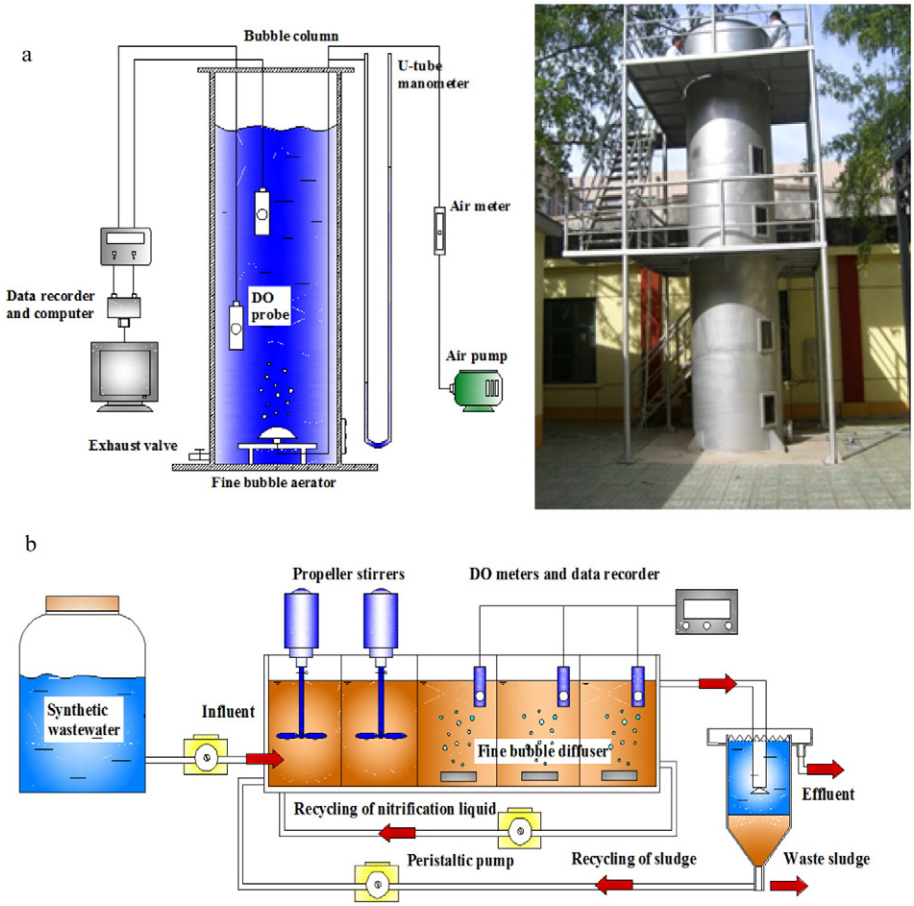

Fig. 1 – Experimental set-up design. (a) System for oxygen transfer testing; (b) an anoxic–oxic activated sludge system.

nitrification and denitrification. The initial concentration of MLSS was about 3500 mg/L, and different MLSS levels were obtained during testing by adding seed sludge. The temperature of the mixed liquor was maintained at approximately 20°C during experiments.

Nitrifier growth kinetics tests were performed in an anoxic-oxic activated sludge reactor with working volume of 37.5 L. A secondary settler with working volume of 24 L (Fig. 1b) was used for solid separation. The reactor was divided into five chambers. The first two chambers with propeller stirrers (propeller diameter = 5 cm; speed of stirring = 150 r/min) were anoxic zones, while the subsequent three chambers were used as aerobic zones. The volume ratio of anoxic to aerobic zones was 2:3. Fine bubble diffusers were used in aerobic zones. To construct kinetic curves as a function of DO concentration, the same LDO fluorescent DO electrodes were used in these reactors and DO concentration was adjusted to a target value using an air meter.

Liquid and sludge flow were controlled *via* peristaltic pumps. The hydraulic retention time (HRT) of one complete process was 9 hr. Return sludge was pumped continuously from the settler to the aeration tank, at a proportion of 150% of influent flow. The recycling ratio of nitrification liquid from aerobic to anoxic zones was 200%. Reactors were operated for 200 days, and SRT was maintained at day 15. To achieve a target SRT, waste sludge was withdrawn daily directly from the aeration tank. Each DO condition was run for at least 3 SRTs to establish steady state conditions. The temperature of the mixed liquor was maintained at 25°C.

Seed sludge was the same as that used in the aeration test. The reactor was fed with synthetic wastewater, which mainly consisted of glucose, NH_4Cl, and KH_2PO_4. COD, NH_4^+-N, and PO_4^{3-}-P were controlled at 250–400 mg/L, 45–60 mg/L, and 5–8 mg/L, respectively. The nutrient solution used in this experiment consisted of $C_2H_3NaO_2{\cdot}3(H_2O)$ (0.67 g/L), KH_2PO_4 (0.07 g/L), NH_4Cl (0.2 g/L), $CaCl_2$ (1.3 mg/L), $NaHCO_3$ (0.09 g/L), and $MgSO_4{\cdot}7H_2O$ (6 mg/L).

1.2. *Determining nitrifier growth kinetic parameters*

1.2.1. *Determining oxygen half-saturation constant*

Before determining the oxygen half-saturation constant, nitrification rates were measured as per the following method. First, reactors were fed synthetic wastewater to establish an initial ammonium concentration of 100 mg/L. After initial sampling, the reactors were allowed to consume substrate for 15 min, 0.5 hr, 1 hr, 1.5 hr, 2 hr, and 3 hr. At the end of this period, the reactors were re-sampled to determine ammonium uptake. Samples of approximately 15 mL were taken from each reactor for ammonia determination using 0.45 μm syringe filters (F&H, Guang Zhou, China). The non-linear relationship between DO and ammonia oxidation rates is captured by Monod kinetics

(Eq. (1)). When the ammonia concentration is sufficient, oxygen becomes the limiting substrate, and the oxygen half-saturation constant can be calculated as follows:

$$V = \frac{V_m \cdot S}{K_{o,s} + S} \quad (1)$$

where V_m is maximum reaction rate; $K_{o,s}$ is oxygen half-saturation constant; and S is substrate concentration.

By measuring the ammonia oxidation rate and nitrification rates of different DO concentrations, $K_{o,s}$ of AOB or NOB can be obtained. The concentrations of oxygen assayed were 0.3, 0.5, 0.8, 1, 2, 4 mg/L; half of the DO values were lower than 1 mg O_2/L in order to capture growth dynamics at low oxygen levels accurately. The DO level of 2 mg/L represents the current design oxygen concentrations in nitrifying systems, and 4 mg/L represents maximum reaction rates. This kinetic parameter was obtained for each reactor by best-fitting Eq. (1) using OriginPro 8.5 (OriginLab, USA).

1.2.2. Determining AOR_{max} and NOR_{max}

It is difficult to determine the real quantity of ammonia oxidizers and nitrite oxidizers in activated sludge. In this study, maximum ammonia and nitrite oxidation rates (AOR_{max} and NOR_{max}) were used to indicate nitrifier biomass concentrations and nitrification capacity, respectively. A pulse-flow aerobic/anaerobic respirometer system (PF-8000 Respirometer System and Application, Fayetteville, Arkansas, USA) was used to detect AOR_{max} and NOR_{max}. These batch respirometric tests were performed in the following way.

An activated sludge sample (of 500 mL) was placed in a reaction flask and bubbled with air for 3–5 hr to ensure an endogenous state. Subsequently, 5 mL of NH_4Cl solution (NH_4^+-N concentration of 4000 ± 50 mg/L) or 5 mL of $NaNO_2$ solution (NO_2-N concentration of 4000 ± 50 mg/L) were introduced into the reaction flask to enable AOR or NOR measurement. The reaction flask was placed in the water bath of the respirometer system at a constant temperature of 25°C and stirred at a speed of 500 r/min. After complete mixing, ammonia and nitrite concentrations were determined. Meanwhile, carbon dioxide generated by biomass was adsorbed by a KOH scrubber in a reactor and the same volume of oxygen was then supplied to the reactor to compensate for the pressure decrease in the headspace. At equilibrium, the oxygen supply rate was equal to the OUR of biomass. OUR was recorded every 6 min through the control module and a computer. During the test, $NaHCO_3$ solution (1 mol/L) was added into the reaction flask to ensure that pH was maintained at 7.5–8.5. Subsequently, 50 mL duplicate samples of mixed liquor were taken to determine concentrations of total suspended solids (TSS) and volatile suspended solids (VSS) in each reactor. Independent experiments were carried out for each DO concentration level and bioreactor. Finally, reaction ammonia and nitrite concentrations were determined, and the standard respirometric procedure (APHA et al., 2005) was used to measure SOUR values.

1.3. Chemical analysis methods

COD was analyzed using a rapid COD tester (WTW, PhotoLabS6, Germany). Ammonia (NH_4^+-N), nitrate (NO_3^--N), nitrite (NO_2^--N), total nitrogen (TN), MLSS, and sludge volume index (SVI) were determined according to APHA standard methods (APHA et al., 2005). The samples for NH_4^+-N were filtered with 0.45 mm membrane filters before analysis.

2. Theoretical aspects

2.1. Oxygen mass transfer kinetics in clean water and in-process

The K_La and OTR were determined according to the standard method for the measurement of oxygen transfer in clean or tap water (ASCE, 2000), calculated as follows:

$$\frac{dC_{O_2}}{d_t} = K_La\left(C^*_{\infty,O_2} - C_{O_2}\right) \quad (2)$$

$$OTR = K_La\left(C^*_{\infty,O_2} - C_{O_2}\right)V \quad (3)$$

where, K_La (hr^{-1}), global oxygen transfer coefficient in clean water; C_{O2} (mg/L) DO concentration at time t, $C^*_{\infty O2}$ (mg/L), DO saturation concentration; V (L), working volume.

Oxygen transfer efficiency (OTE) was calculated using Eq. (4) based on the measured OTR and air flow rate:

$$OTE = \frac{OTR}{0.28 \times Q} \quad (4)$$

where, Q (m^3/hr), air flow rate; 0.28, unit quality of oxygen in air.

In the activated sludge reactor, because of the microbial respiration and DO concentrations in the influent and effluent, the oxygen balance in the aeration basin was represented as follows (ASCE, 1997):

$$\frac{dC_{O_2}}{dt} = \frac{Q_w}{V}(O_i - O_e) + K_La_f\left(C^*_{\infty f,O_2} - C_{O_2}\right) - OUR_{ex} - OUR_{end} \quad (5)$$

where, K_La_f, global oxygen transfer coefficient in wastewater; $C^*_{\infty f,O2}$ (mg/L) DO saturation concentration during the process conditions; OUR_{ex} (mg/(L·hr)), exogenous oxygen uptake rate (OUR) of the activated sludge; OUR_{end} (mg/(L·hr)), endogenous OUR; Q_w (L/hr), inflow quantity; O_i (mg/L), DO in the influent; O_e (mg/L), DO in the effluent; V (L), aerobic sewage tank volume; α represents the influence degree of factors in wastewater on oxygen mass transfer, calculated as follows based on the determined K_La and K_La_f:

$$\alpha = \frac{K_La_f}{K_La} \quad (6)$$

2.2. Nitrifier growth kinetic parameters in the overall nitrification reaction

Operational DO concentrations in an advanced treatment plant are usually determined by nitrification needs, because nitrifiers are less competitive in utilizing DO than heterotrophic bacteria in activated sludge (Metcalf and Eddy Inc., 2003). The kinetic parameters of nitrifiers were therefore investigated though *in situ* experiments in this study. The oxygen half-saturation constant K_s can be obtained from the Monod kinetics equation (Eq. (1)).

The maximum ammonia and nitrite oxidation rates in the activated sludge can be conveniently measured, and ammonia oxidation can be considered as a zero order reaction when the ammonia concentration is sufficient in a batch respirometric test. Based on Eq. (7), the maximum ammonia oxidation rate ($k_{NH}X_{NH}$) and the maximum nitrite oxidation rate ($k_{NO}X_{NO}$) can be estimated through OUR:

$$AOR_{max} = k_{NH}X_{NH} = \frac{OUR_{max,NH}}{3.43–1.42Y_{NH}} \quad (7)$$

$$NOR_{max} = k_{NO}X_{NO} = \frac{OUR_{max,NO}}{1.14–1.42Y_{NO}} \quad (8)$$

The stoichiometry of the nitrification process is referred to the previous report of Liu and Wang (2012).

3. Results

3.1. Effluent quality under high DO and low DO conditions

The A/O reactor was operated for 100 days and maintained at a steady state with 1 mg/L DO conditions for 45 days. Fig. 2 shows the treatment performance of the reactor under different DO conditions. Influent COD concentrations were in the range of 250–400 mg/L, and NH_4^+-N was in the range of 45–60 mg/L. As can be noted from Fig. 2a, effluent COD concentrations were <50 mg/L (class A, urban sewage treatment plant nutrient discharge standard of China, GB 18918-2002) under both high and low DO conditions, and the average COD removal efficiency was >85%. The decrease in DO from 1.0 to 0.5 mg/L therefore did not affect effluent COD quality.

Fig. 2b and c shows nitrification performance under different DO conditions. As shown in Fig. 2b, under high DO conditions, effluent NH_4^+-N concentrations were mostly <0.5 mg/L. After further reducing DO to 0.5 mg/L, effluent NH_4^+-N concentrations immediately increased to about 12 mg/L. However, after a few days, effluent NH_4^+-N concentrations again decreased to approximately 0.5 mg/L, indicating the gradual recovery of nitrification under low DO conditions. Average COD removal efficiency was above 85% in both cases.

As can be noted in Fig. 2c, effluent TN concentration removal efficiency was less stable, with concentrations >20 mg/L in some cases during the initial operation period. However, during the second SRT period, effluent TN concentrations were mostly <15 mg/L (class A). After decreasing DO to 0.5 mg/L, effluent TN concentrations decreased to approximately 10 mg/L. Average TN removal efficiency was about 85.5% and 88.0% under high and low DO conditions, respectively. Effluent NO_3^- concentrations were in the range of 0.7–19 mg/L under high DO conditions, and in the range of 0.16–9 mg/L under low DO conditions. Higher DO in the aeration tank resulted in higher DO in returned sludge, leading to lower TN removal efficiency. Low DO operation can therefore decrease the DO of returned sludge, which is of benefit to the denitrification process.

In reactors with DO concentrations of 1 and 0.5 mg/L, NO_2^- concentrations were in the range of 0–1 mg/L in both cases,

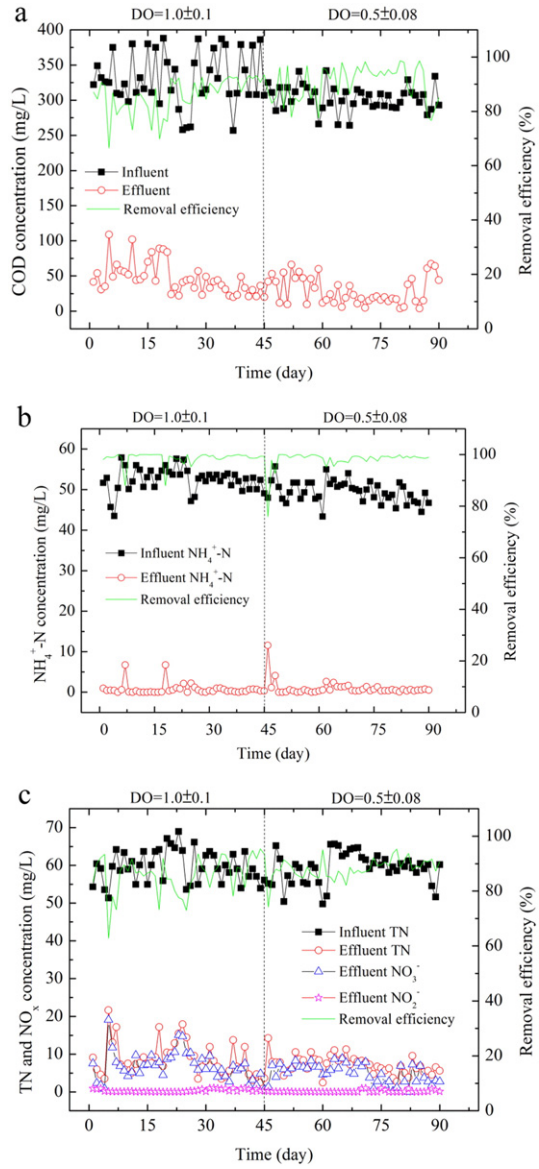

Fig. 2 – Treatment performance under different DO conditions. (a) COD, (b) NH_4^+-N, (c) total nitrogen (TN) and (d) NO_x.

indicating almost complete nitrification after one SRT period of operation. In fact, ammonia and nitrite concentrations were maintained at <0.5 mg-N/L and <0.3 mg-N/L in most cases under both sets of DO conditions (Fig. 2a), suggesting that nitrifiers were adapted to the oxygen-deficient environment and that microbial properties were significantly resilient to the impact of low DO. Above all, these results indicate that DO concentrations in the aeration basin can be gradually reduced to a very low level during long-term operation for energy saving purposes.

3.2. Oxygen mass transfer dynamics under different operating conditions

Airflow rate (Q_{air}) and sludge concentrations (MLVSS) are two of the most important controllable indicators impacting aeration during the operation of WWTPs. In this pilot

experiment, K_La values were measured independently under different airflow rates and MLVSS levels. In order to compare different diffusers, the airflow rate was represented by that of a specific aeration area (Q'_{air}, $m^3/(m^2 \cdot hr)$). As can be noted in Fig. 3, K_La increased with increasing Q'_{air}. When Q'_{air} increased from 58.98 to 235.91 $m^3/(m^2 \cdot hr)$, K_La increased from 0.025to 0.083 min^{-1}, and the OTR increased from 0.145 to 0.483 kg O_2/hr. These results show a good linear relationship between airflow rate and K_La, mostly for two reasons. First, gas holdup increases linearly with increase in airflow rate, indirectly enhancing the gas–liquid contact area. Second, the degree of turbulence of mixed liquid will be greater with faster airflow rate, promoting oxygen delivery from air into water.

Eqs. (9) and (10) express fitting of K_La and OTR as a function of the specific aeration area. Different diffusers used in different conditions produce a different fitting line. High K_La or OTR indicate good aeration diffuser performance, corresponding to strong oxygen mass transfer capacity to meet microbial respiration requirements. The fitting line characterizes aerator performance, which is also an important basis for aeration control.

$$K_La_s = 0.0041 + (3.202 \times 10^{-4})\ Q'_{air} \quad (9)$$

$$OTR = 0.00187 + (2.404 \times 10^{-4}\text{-}3)\ Q'_{air} \quad (10)$$

In addition to airflow rate, MLVSS significantly impacts aeration efficiency. As shown in Fig. 3b, under pilot conditions, when activated sludge concentrations increased from 2000 to 5000 mg/L, K_La declined rapidly. The fitting line is also an important basis for aeration control:

$$K_La_s = -0.975\ MLVSS + 0.926 \quad (11)$$

Raszka et al. (2006) concluded that MLVSS affects oxygen mass transfer through the involvement of organic substances, including bacteria, protozoans, and extracellular polymeric substances (EPS), which substantially affect water content in the mixed phase. The more water is bound by organic substances in activated sludge, the larger the volume occupied by sludge flocs. The volume of sludge flocs or solid content in a heterogeneous reaction system can affect oxygen mass transfer in water (Mena et al., 2005; Henkel et al., 2011a, 2011b). It can therefore be inferred that when microbial metabolism is active, secretion of EPS and SMP would hinder oxygen mass transfer more significantly, leading to greater negative influence.

Fig. 3c shows the results of previous studies by other researchers. Experimental results have shown that α values decline significantly with a rise in MLVSS concentrations. In an experimental study by Henkel et al. (2011a), the relationship between α and MLVSS concentrations proved approximately linear, and the relationship was fitted using linear regression, as follows (the applicable range of MLVSS values is 1–12,000 mg/L):

$$\alpha\ value = -0.062\ MLVSS + 0.972 \pm 0.070 \quad (12)$$

According to previous research, activated sludge concentrations should not be too high in practical operation, as it would lead to rapid decrease in K_La and OTE, leading to high energy consumption to ensure sufficient oxygen supply.

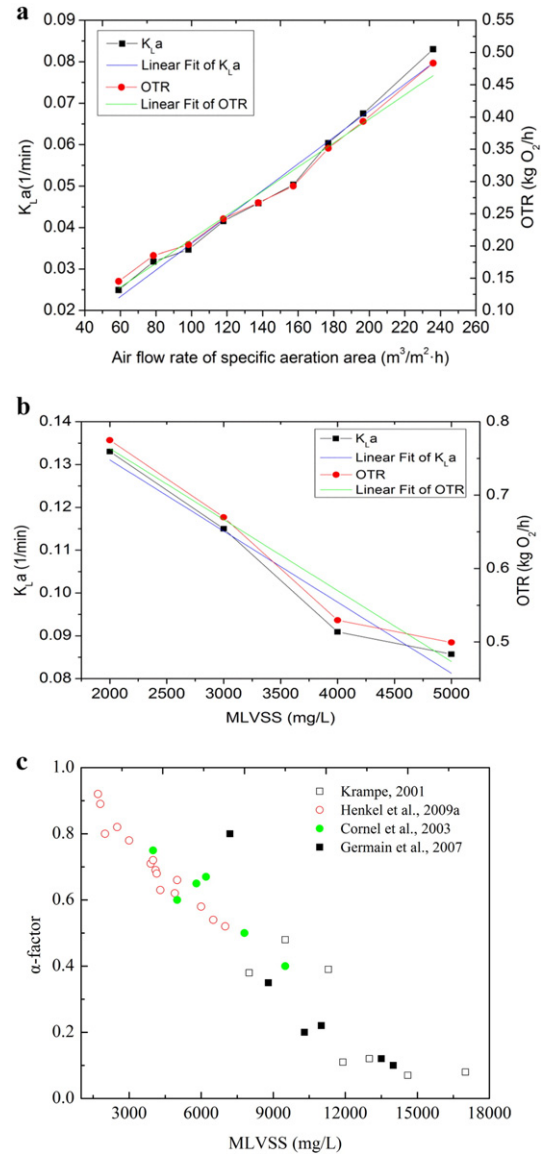

Fig. 3 – Oxygen mass transfer rate under different operating conditions (a) K_La_s and OTR as a function of air flow rate of a specific aeration area; (b) K_La values as a function of MLVSS; (c) relationship between α value and MLVSS from previous studies (Krampe, 2001; Cornel et al., 2003; Germain et al., 2007; Henkel et al., 2009a).

3.3. Growth kinetic parameters of nitrifier communities under high and low DO conditions

Fig. 4 shows nitrification rates (mg NH_4^+-N/(g VSS·hr) and mg NO_2^--N/(g VSS·hr) as a function of DO level for activated sludge cultivated after reaching steady state, with SRTs of 15 days. The relationship conformed to Monod kinetics, as confirmed in previous studies (Mukhopadhyay and Das, 1994). When the activated system was operated at high DO levels (1 mg/L), AOR_m and NOR_m were achieved at 4.28 mg N/(g VSS·hr)and 3.43 mg N/(g VSS·hr), respectively. When DO was decreased to 0.5 mg/L and the system was operated for a long period of time, both AOR_m and NOR_m increased significantly, up to 4.59 mg N/(g VSS·hr) and 3.91 mg N/(g VSS·hr), respectively;

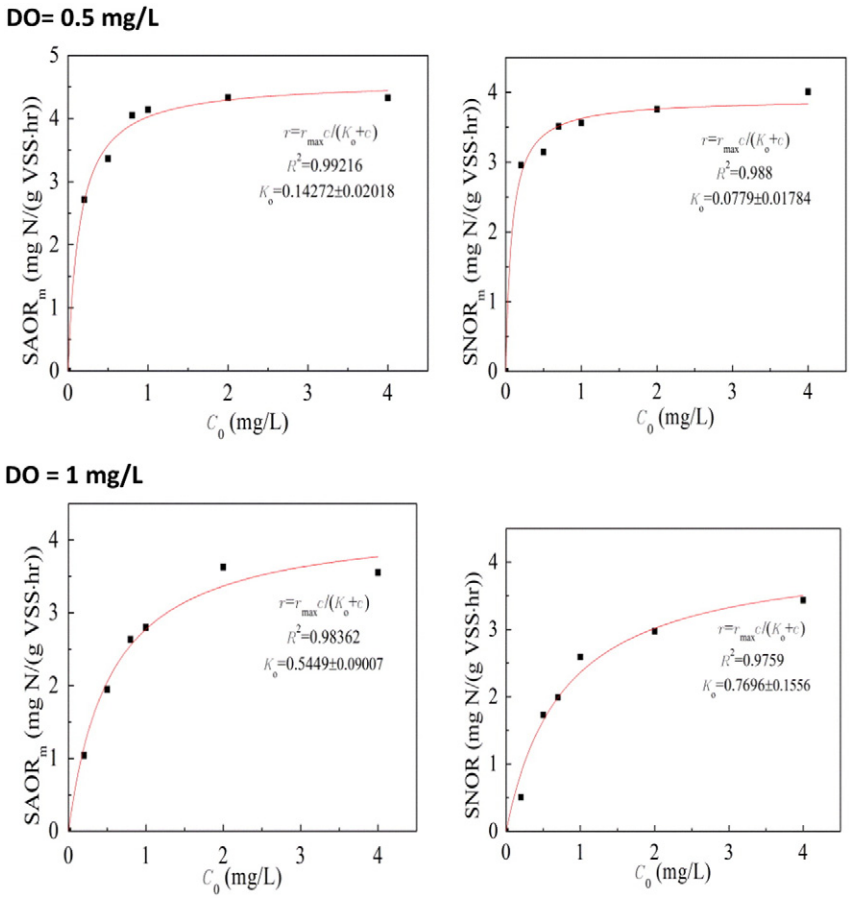

Fig. 4 – Nitrification rates as a function of DO for activated sludge under high and low DO conditions ((1) 0.5 mg/L; (2) 1 mg/L).

low DO nitrification performance was therefore as good as that obtained with the high DO system.

It is well known that low DO adversely affects AOB and NOB growth rates (Park and Noguera, 2004, 2007; Weon et al., 2004). However, researchers have recently hypothesized that the increase in ammonia oxidation capacity under low DO conditions may be due to a high AOB yield. Other researchers have found that the decay rate of AOB and NOB decreases under low DO conditions, while biomass concentrations are expected to increase, thereby increasing sludge nitrification capacity. In our study, nitrifier communities were shown to have higher activity in low DO cultivated environments, enhancing oxygen mass transfer between the gas and liquid phases.

The inflow of the lab-scale test was used as synthetic wastewater. Thus there were differences in the aerobic nitrifying sludge nature between the lab experiment and actual WWTPs, such as in floc size, AOR, NOR and SVI. In general, the floc sizes of actual WWTPs were mainly about 200 μm. The majority of the floc sizes were in the range from 300 to 600 μm under low DO conditions in the lab-scale reactor. Therefore, flocs tended to be larger in lab-scale systems than in full-scale plants. AOR$_m$ and NOR$_m$ of activated sludge in lab experiment were lower than actual aerobic nitrifying sludge, just as in the results of Liu and Wang (2013). The SVI was in the range of 180 to 200 mL/g in the lab-scale test in low DO conditions, which was larger than in actual WWTPs. A possible reason is that synthetic wastewater is rich in easily degradable organic matter and low in suspended solids. In addition, the nutritional components of the synthetic wastewater were not as abundant as in raw sewage.

Based on the method outlined in Section 3.2, Table 1 shows the nitrification kinetic parameters of activated sludge under different DO culture conditions in batch tests. The oxygen half-saturation constants K_o of AOB and NOB were both lower under low DO conditions than under high DO conditions, indicating that nitrifier communities cultivated under low DO conditions have a better capacity to utilize oxygen. Otherwise, NOB were more competitive in low DO environments than AOB because of lower K_o; it is therefore easier to eliminate NOB with higher DO conditions for better anammox or simultaneous operation of nitrification–denitrification processes. This indicates that enrichment of AOB and NOB biomass occurred, leading to more nutrient removal (Bellucci et al., 2011). The complete nitrification achieved with a DO

Table 1 – K_o and OUR$_{max}$ of nitrifiers under different DO culture conditions.

Growth kinetic parameters	DO = 1 mg/L		DO = 0.5 mg/L	
	AOB	NOB	AOB	NOB
K_o (mg/L)	0.54 ± 0.09	0.77 ± 0.16	0.14 ± 0.02	0.08 ± 0.02
AOR$_m$ or NOR$_m$ (mg O_2/(L·hr))	11.01	3.64	13.94	4.25

DO: dissolved oxygen; OUR: oxygen uptake rate.

concentration of 0.5 mg/L was therefore likely due to sludge having increased its nitrification capacity, reducing the adverse effect of low DO on the nitrification rate. High specific ammonium oxidation rate (SAOR) and specific nitrite oxidation rate (SNOR) values could lead to a lower DO balance between OUR and OTR, facilitating less energy-consuming operation.

4. Discussion

4.1. Model aeration dynamic assumptions in different activated sludge systems

At present, high air flow rates or high K_La diffusers are used in actual operation of WWTPs for better aeration performance. When influent water quality is constant and SRT is stable, the SOUR of activated sludge is constant; increasing sludge concentration can improve the OUR. However, high MLVSS values will reduce K_La, and it is therefore important to first comprehensively explore the relationship between aeration performance and sludge activity parameters. As shown in Eq. (2), when a steady state is achieved in an aeration basin, $\frac{dC_{O_2}}{dt} = 0$ and Eq. (13) can be obtained:

$$K_La_f\left(C^*_{\infty f,O_2} - C_{O_2}\right) = OUR_{ex} + OUR_{end} \quad (13)$$

where C_{O2} is the equilibrium DO value of the process.

When there is a balance between oxygen demand and supply, the oxygen mass transfer rate is equal to the OUR of sludge, and the equilibrium DO concentration C_{O2} C_{O2} of the aeration basin will have been achieved. The concentration of C_{O2} is a very important dynamic parameter for the oxygen mass transfer process, affecting the oxygen consumption ability of biomass. The relationship between OUR and DO concentrations fits the Monod kinetic model, while the oxygen supply rate conforms to a more robust linear model. A balance between oxygen demand and supply can help avoid unnecessary excess airflow; the key is maintaining this balance at a low steady state DO concentration.

The discussion of aeration performance under different conditions is based on a model with the following assumptions: aeration dynamic testing performed in the pilot test device, and five groups of aeration diffusers with different K_La values used for the same process conditions. Specific parameter assumptions were calculated as shown in Table 2. The theoretical maximum OTR was calculated by Eq. (3), assuming that the equilibrium DO concentration is zero.

A series of batch tests were performed under different DO conditions according to the methods of Section 1.1. The nature of activated sludge is classified into two cultivated conditions at different DO concentrations in the long-term (DO = 0.5 mg/L cultivated condition referred to as "low DO system", DO = 1.0 mg/L cultivated condition referred to as "high DO system"), with Table 1 and Fig. 4 showing specific reference information for small-scale tests. The MLVSS of activated sludge was maintained at 3000 mg/L when the test was conducted.

4.2. Aeration efficiency of different activated sludge systems

Based on the assumptions above, at different DO levels, OTR and AOR can be calculated according to Eqs. (1) and (3), and the equilibrium DO value C_0 can be calculated according to Eq. (13). The balance between oxygen demand and supply is plotted in Fig. 5, representing activated sludge activity and the oxygen mass transfer rate at different DO concentrations.

In all the different activated sludge systems, DO eventually reached an equilibrium value at steady state, and the OTE value using different diffusers could be calculated. As can be noted from Table 3, in the same activated sludge system with an airflow rate of 5 m^3/hr, the performance of the five diffusers gradually improved (being enhanced by about 50%), but the increase in OTR or OTE gradually declined. For example, in the low DO system, the OTE of diffuser #2 increased by about 48.8% compared to diffuser #1, but the improvement in OTE of diffuser #4 over diffuser #3 sharply declined to 26.8%, while that of diffuser #5 was only 4.6% greater than of diffuser #4. Similarly, in the high DO system, diffuser #5 only enhanced OTE by 7.2% compared to diffuser #4. This indicates gradually decreasing efficiency with upgrading of the aeration diffuser. The reason is that the nature of activated sludge remains constant and OUR changes little during operation; oxygen delivered to the liquid therefore cannot be significantly consumed, resulting in an increase in equilibrium DO concentrations. The oxygen mass transfer driving force is therefore reduced, weakening the benefits obtained through improvement of aeration performance.

Moreover, significant investment of material and financial resources may be needed to increase the K_La value of a diffuser by 50% in practice; however, as shown in Table 3, the actual OTE of the aeration system may only improve by 4.6%. For a particular activated sludge system, using a diffuser with the highest oxygenation performance is therefore not the most economical method of improving aeration efficiency, as the optimal K_La range is closely related to the nature of the activated sludge.

Table 2 – Assumptions for five groups of aeration systems.

Diffuser number	#1	#2	#3	#4	#5
K_La (hr^{-1})	2.4	3.6	5.4	8.1	12.15
Theoretical maximum OTR (mg/hr)	203,520	305,280	457,920	686,880	1,030,320
Airflow rate (m^3/hr)	5				
Saturated DO in wastewater (mg/L)	8				
Aeration basin working volume (m^3)	10.6				
Water depth (m)	6				

OTR: oxygen transfer rate; DO: dissolved oxygen.

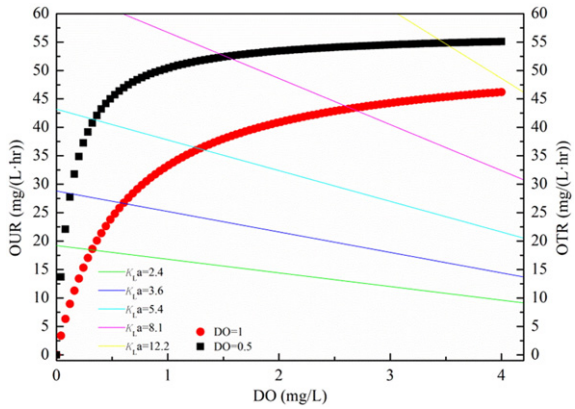

Fig. 5 – Demand and supply balance of oxygen under two kinds of DO cultured activated sludge at different aeration performance levels.

As shown in Table 4, using the same diffuser, the OTE of the low DO activated sludge system was higher than of the high DO system, with an increase in the range of 3.3%–20.9%. The reason is that higher SOUR can be obtained under low DO culture conditions, resulting in greater oxygen consumption and lower equilibrium DO value with the same MLVSS value. Under low DO conditions, the oxygen mass transfer driving force increased to improve OTE. On the other hand, the low DO system could also perform better using a better diffuser. For example, the OTE achieved with diffuser #3 was 31.3% and 27.4% in low DO and high DO systems respectively, with OTE enhancement of 14%, while the OTE achieved with diffuser #4 was 39.7% and 32.8%, respectively, with OTE enhancement of 20.9%; diffuser #4 thus is ideal to maximize the benefits of low DO operation.

The selection of diffusers should therefore take into account the OUR of activated sludge. In theory, the efficiency resulting from upgrading of aeration diffusers will be more apparent before the inflection point of OUR and the Monod kinetic model curve, with this increase in efficiency then gradually declining beyond the inflection point.

Table 4 – Aeration system performance under different DO culture conditions.

Diffuser number	OTE with DO = 0.5 mg/L culture conditions (%)	OTE with DO = 1 mg/L culture conditions (%)	OTE improvement level (%)
#1	14.0	14.4	3.3
#2	20.2	21.5	6.4
#3	27.4	31.3	14.0
#4	32.8	39.7	20.9
#5	35.2	41.5	18.0

OTE: oxygen transfer efficiency; DO: dissolved oxygen.

4.3. Aeration efficiency at different nutrient loads

In this part of the study, aeration efficiency was evaluated under high and low DO cultivation conditions, with different influent ammonia concentrations of 30, 50, and 80 mg/L, respectively. Aeration diffuser performance remained the same as with diffuser #1, while K_La varied with different airflow rates, as per Eq. (9). Effluent ammonia concentrations were 5 mg/L, as per standard class IA, (urban sewage treatment plant nutrient discharge standard of China, GB 18918-2002). The HRT of the aerobic tank was presumed to be 8 hr. Theoretically, 4.57 g of oxygen are needed to completely oxidize 1 g of ammonia–nitrogen (ammonia-N) into nitrate, so the oxygen demand per unit volume influent and air flow rate can be calculated as per Table 5.

Based on the results above, given the same aeration performance, the low DO system required less air than the high DO system while removing same quantity of ammonia. For example, when influent ammonia concentrations were 30 mg/L, the effluent was also of class IA quality; however, the airflow rate needed in the low DO system was 2.02 m^3/hr, representing savings of 2.6% of air volume compared with 2.07 m^3/hr in the high DO system. When influent concentrations were raised to 80 mg/L, the low DO system could reach the targeted ammonia quality with an airflow rate of 7.01 m^3/hr. Due to the limited OUR of activated sludge in the high DO system, the airflow rate should be as high as 9.82 m^3/hr. The

Table 3 – Changes in aeration efficiency resulting from adoption of different diffusers in activated sludge system.

Diffuser number	Equilibrium DO with low DO culture conditions (mg/L)	OTR	OTE	K_La improvement level (%)	OTE improvement level (%)
#1	0.07	201,853.3	14.4	-	-
#2	0.13	300,347.2	21.5	50	48.8
#3	0.35	438,081.2	31.3	50	45.9
#4	1.53	555,294.8	39.7	50	26.8
#5	3.49	580,768.4	41.5	50	4.6
Diffuser number	**Equilibrium DO with high DO culture conditions (mg/L)**	**OTR**	**OTE**	**K_La improvement level**	**OTE improvement level**
#1	0.32	195,405.2	14.0	-	–
#2	0.6	282,257.6	20.2	50	44.4
#3	1.29	384,143.1	27.4	50	36.1
#4	2.65	459,119.8	32.8	50	19.5
#5	4.18	492,267.5	35.2	50	7.2

DO: dissolved oxygen; OTR: oxygen transfer rate; OTE: oxygen transfer efficiency.

Table 5 – Oxygen demand to achieve Class I A with different DO culture conditions.

Influent ammonium concentration (mg/L)	Oxygen demand to achieve Class I A (mg/(L·hr))	DO culture conditions	Equilibrium DO	Airflow rate (m^3/hr)
30	14.3	Low DO	0.05	2.02
		High DO	0.22	2.07
50	25.7	Low DO	0.11	3.92
		High DO	0.56	4.18
80	42.8	Low DO	0.40	7.01
		High DO	2.50	9.82

DO: dissolved oxygen.

air volume savings of the low DO system were up to 28.6% compared to the high DO system. Thus, with more nutrients for degradation, more air will be saved.

Fig. 6 shows the equilibrium DO of high and low DO systems based on the oxygen supply and consumption balance. It is apparent that when removing the same amount of nutrients from a given aeration system, the low DO activated sludge system will have lower equilibrium DO than the high DO system, leading to high-efficiency of oxygen mass transfer and to it being more economical in terms of energy saving. If the activated sludge of a WWTP has low activity, there will be a significant decline in oxygen utilization and an increase in the airflow rate to achieve a given nutrient removal target, resulting in substantial energy waste.

4.4. Low DO operation for aeration optimization over short- and long-terms

Based on the analysis above, aeration optimization is a comprehensive control process that takes into account diffuser performance and the nature of activated sludge. The following parameters should be considered: (1) aeration performance (airflow rate Q_{air}, K_La); (2) nature of activated sludge (MLVSS, OUR_{max}, OUR_{end}); and (3) system operating parameters (DO concentration, SRT).

High OUR leads to a low DO level in liquid, promoting oxygen transfer because of the high mass transfer driving force. Thus, low DO sewage treatment conditions will lead to significant energy saving.

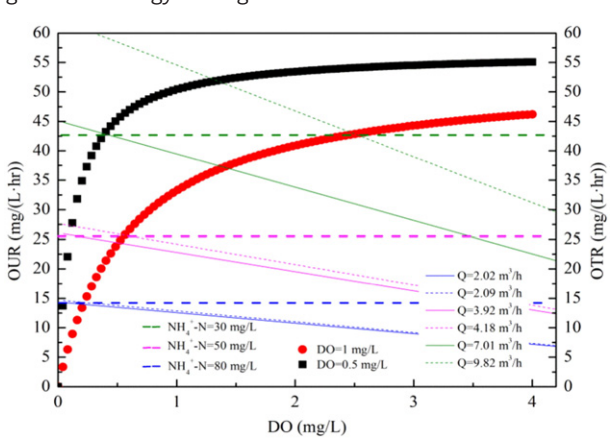

Fig. 6 – Demand of air flow rate with different inflow ammonia concentration in low DO and high DO activated sludge systems.

Over short-term operation, the nature of activated sludge does not change very much. Based on the discussion in Section 3.3, the OUR–DO curve can be obtained as per the Monod kinetic model. The theoretically optimal DO value is the inflection point of the OUR–DO curve. Modification of the aeration diffuser before the inflection point would produce significant benefit, with this gradually decreasing beyond the inflection point.

As shown in Fig. 7a, if the current DO is lower than the optimal DO, there is significant potential for removing more nutrients. If the current DO is higher than the optimal DO, the airflow rate is too high and there is significant potential for energy saving. In our study, high MLVSS values increased OUR

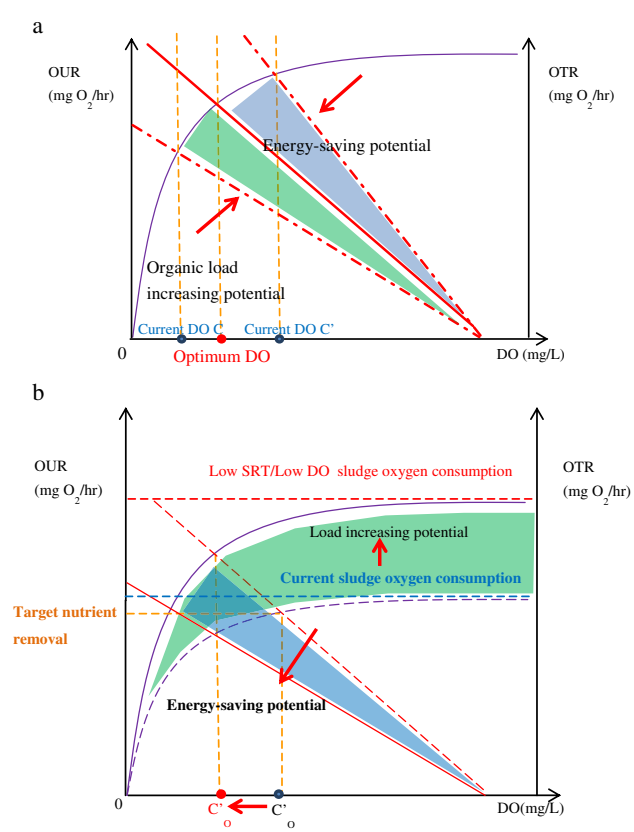

Fig. 7 – Low DO operation for aeration optimization. (a) Aeration optimization over the short-term; (b) aeration optimization over the long-term; C and C′ are operating DO concentration in different air flow rate; C'_o is optimal DO in high DO conditions, and C_o is optimal DO in low DO conditions.

but reduced the K_La value. Thus, two curves of MLVSS as a function of K_La and OUR should be explored for different WWTPs, and the optimal MLVSS should be controlled at the intersection point of the two curves.

Over long-term operation, the OUR of activated sludge improves and the DO concentration of the aeration tank should be gradually reduced to save energy. Based on the results of this study, OUR can be improved by changing the nitrifier community through long-term low DO culture. Long-term low DO could result in good nitrification performance because both AOB and NOB in activated sludge are enriched to increase sludge nitrification capacity (Liu and Wang, 2013). Arnaldos et al. (2013) also showed that the SOUR values of a low DO reactor (0.1 mg/L) were higher than those of a high DO reactor (near saturation oxygen concentration), and stable and complete nitrification was achieved after an acclimation period of approximately 140 days.

As shown in Fig. 7b, if OUR is low, SRT should be reduced to a suitable condition for higher nitrification capacity, or stabilized for 2–3 SRTs under low DO conditions, enabling the structure and properties of microbial populations to acclimatize. From high DO to low DO there is significant load-increasing potential because of the increase in OUR. If there is a target nutrient amount to be removed, long-term low DO conditions could enable larger air volume savings than a high DO system. The aeration control strategy mentioned above is also useful for appropriate setting of the oxygen point and for operation of low DO treatment technology.

5. Conclusions

(1) Long-term low DO culture conditions reduce the oxygen half-saturation constant of the adapted microbial population, with clear improvement in the OUR of activated sludge. Analysis results have shown that the OTE of a low DO system can be enhanced by about 3.3%–20.9%, compared with that of a high DO system. (2) High MLVSS values will lead to low K_La, and MLSS should therefore be maintained within an optimum range to ensure a high rate of nutrient degradation and high OTE. (3) When the OUR of activated sludge is low, the potential for energy savings by improving aeration performance is limited. (4) Low DO operation for aeration optimization was aimed at improving the OUR of the activated sludge system. Changing the nature of activated sludge over long-term cultivation can decrease operational DO concentrations and reduce the energy consumption of WWTPs.

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